Physics of the Earth's Space Environment

Gerd W. Prölss

Physics of the Earth's Space Environment

An Introduction

With 263 Figures
Including 4 Color Figures

Springer

Professor Dr. Gerd W. Prölss
Universität Bonn
Institut für Astrophysik und Extraterrestrische Forschung
Auf dem Hügel 71
53121 Bonn, Germany

Translated by: Dr. Michael Keith Bird
Universität Bonn
Institut für Radioastronomie
Auf dem Hügel 71
53121 Bonn, Germany

Cover picture: Dayglow and aurora imaged from the DE1 satellite at an altitude of about 20,000 km. Further information may be found in Sections 3.3.8 and 7.4 (L.A. Frank, University of Iowa).

Library of Congress Control Number: 2004102968

ISBN-13: 978-3-642-05979-7   e-ISBN-13: 978-3-642-97123-5
DOI: 10.1007/978-3-642-97123-5

Springer is a part of Springer Science+Business Media
springeronline.com

Softcover reprint of the hardcover 1st edition 2004

Print data prepared by LE-TeX Jelonek, Schmidt & Vöckler GbR, Leipzig
Cover design: Erich Kirchner, Heidelberg

Printed on acid-free paper   57/3141/ts   5 4 3 2 1 0

Preface

This book was written for readers interested in learning about the disciplines, methods and results of space research, perhaps because they happened upon the field during the course of their higher education or professional career, or perhaps because they simply feel an urge to know more about the space environment of the Earth. The present monograph is based on lectures covering the same topic, which have been held regularly over the past years at the University of Bonn. Like the lecture series, the book is directed at a relatively broad group of students and interested laypersons, the only prerequisite being knowledge of fundamental physics and mathematics, as usually acquired from introductory college courses in science or engineering curricula. More specific knowledge is derived in association with each phenomenon considered. These derivations are kept as simple as possible, adhering to the principle that, when conflicts arise, physical insight is preferable to mathematical precision. As a rule, I strived to avoid the trite phrase 'It may be easily shown that ... ' and tried to present all derivations in readily verifiable steps, even if this may seem somewhat tedious to the more advanced readers. Also serving clarity and insight are the many illustrations, which do indeed often say more than 'a thousand words'.

Our knowledge of the Earth's space environment has grown exponentially during the last few decades and an attempt to cover all aspects of the field would extend way beyond the scope of an introductory text. Acknowledging this fact, the book does contain some unavoidable gaps and even topics of special interest to the author have been omitted for lack of space. In particular, measurement techniques, although constituting a cornerstone of space research (and of physics in general), could only be described in passing. We content ourselves here with presenting the experimental results and then trying to explain the underlying physics on the basis of simple reasoning and argumentation. It is fair to say that this introduction to the field will have fulfilled its purpose if its readers are inspired to investigate a topic in more detail on their own, referring to the pertinent literature.

It is a pleasure to thank all those who directly or indirectly participated in the preparation and production of this book. I would like to thank my mentor W. Priester and my colleagues M. Roemer, H.J. Fahr and H. Volland for their support and the pleasant work environment in our institute. Parts of this book were reworked during a lecture series presented at the University of Innsbruck and during a research fellowship at the University of Nagoya. I extend my sincere gratitude here to colleagues M. Kuhn and Y. Kamide for the invitations. Valuable suggestions and various forms of assistance were provided by colleagues and coworkers S.J. Bauer, M.K. Bird, H. Fichtner, G. Lay, C.A. Loewe, K. Schrüfer, R. Treumann and S. Werner. I would like to make special mention of contributions from S. Noël, M. Kilbinger, B. Kuhlen, J. Pielorz and B. Winkel, who competently and patiently edited the manuscript into its final form. Without their help this book would surely have been a never ending story.

Bonn, December 2003 *Gerd W. Prölss*

Contents

List of Frequently Used Symbols

A	area
α	generic angle; pitch angle
$\vec{\mathcal{B}}$	magnetic flux density, here denoted as magnetic field
$\mathcal{B}_{00}$	Earth's equatorial surface magnetic field intensity
$\vec{c}$	random velocity (thermal velocity, peculiar velocity)
c_0	speed of light
c_p, c_V	specific heat capacity at constant pressure, volume
χ	zenith angle; spiral angle
d	thickness; transport term in the equations of balance
D	diffusion coefficient; declination
e	electron
e	elementary charge; base of the natural logarithm
E	energy
$\vec{\mathcal{E}}$	electric field
ε_0	permittivity of free space
ε_r	relative permittivity (dielectric constant)
f	degree of freedom; frequency
f	distribution function
$\vec{F}$	force
$\vec{F}^*$	force per unit volume
$\vec{g}$	gravitational acceleration ($\vec{g}_E, \vec{g}_S$: terrestrial, solar acceleration)
g	velocity distribution function
G	gravitational constant
γ	adiabatic exponent
γ^*	polytropic index
h	height (altitude)
h_P	Planck constant
$h(c)$	speed (velocity magnitude) distribution function
H	scale height; horizontal component of the Earth's magnetic field
$\vec{\mathcal{H}}$	magnetic field
I	momentum; inclination
$\vec{\mathcal{I}}$	current
$\vec{\mathcal{I}}^*$	surface current density

$\vec{j}$ current density
J_X ionization rate coefficient for the species X
k Boltzmann constant
$k_{s,t}$ reaction constants
K generic constant; eddy diffusion coefficient
κ heat conductivity
l length; loss rate per unit volume
$l_{1,2}$ mean free path
λ wavelength; geographic, heliographic longitude
L shell parameter
$\mathcal{L}$ induction constant
$\ln \Lambda$ Coulomb logarithm
m particle mass
m_u atomic mass unit
M generic mass (M_E, M_S: mass of Earth, Sun); Mach number
$\mathcal{M}$ mass number (atomic, molecular)
$\vec{\mathcal{M}}$ magnetic dipole moment ($\vec{\mathcal{M}}_E$: Earth; $\vec{\mathcal{M}}_g$: gyromoment)
μ_0 permeability of free space
n particle number density
n_{ref} reference density; index of refraction
$\hat{n}$ surface normal
N number of particles
$\mathcal{N}$ column density
$\nu_{1,2}$ collision frequency ($\nu_{1,2}^{Cb}$: Coulomb collision frequency)
$\nu_{1,2}^*$ momentum transfer collision frequency (frictional frequency)
ω angular velocity; rotation rate
ω_g Brunt-Väisälä frequency
$\omega_{\mathcal{B}}$ gyrofrequency (Larmor frequency)
ω_p plasma frequency
$\Omega_{E,S}$ angular rotation rate of Earth, Sun
p thermodynamic pressure
p_d dynamic pressure
$p_{\mathcal{B}}$ magnetic pressure
p proton
P power
φ latitude
$\vec{\phi}$ flux of a scalar quantity
Φ magnetic flux
q charge per particle; production rate per unit volume
Q heat
$\mathcal{Q}$ electrical charge
r particle radius; radial distance
$r_{\mathcal{B}}$ gyroradius (Larmor radius)
$\vec{r}$ position vector

R_E, R_S	Earth's radius, Sun's radius
ρ	mass density
ρ_c	radius of curvature
s	distance; species index (e, i, n for electrons, ions and neutral gas particles)
$\sigma_{1,2}$	collision, interaction cross section
σ^A	absorption cross section
$\sigma_B, \sigma_H, \sigma_P$	Birkeland, Hall and Pedersen conductivities
t	time
T	temperature (T_∞: thermopause or exospheric temperature)
τ	time constant; period; optical thickness
$\vec{u}$	bulk velocity
U	internal energy
$\mathcal{U}$	voltage
$\vec{v}$	particle velocity
$\vec{v}_S, \vec{v}_A, \vec{v}_{MS}$	velocity of sound, Alfvén velocity, magnetosonic velocity
$\vec{v}_{ph}, \vec{v}_{gr}$	phase, group velocity
V	volume
w	probability
$\mathcal{W}$	work; index for eddy parameter
x, y, z	Cartesian coordinates; ($\hat{x}, \hat{y}, \hat{z}$ unit vectors); variables